NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Air Cooling Research and Development




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State of the Art

Everything on a vehicle is **air cooled**, *ultimately*…

Intermediate liquid cooling loop

[1]

Air cooling can be done… When?... How?

[2,3]

[4,5]

Honda Insight
Power Rating 12 kW

AC Propulsion AC-150
Power Rating 150 kW

Relevance: Challenges/Barriers to Meet Project Goals

Goal: Develop air-cooled thermal management system solutions that help meet DOE's 2015 technical targets on time

Challenges

- **Air is a poor heat-transfer fluid**
  - low specific heat
  - low density
  - low conductivity
- **Parasitic power**
- **Novelty for this application**

Advantages

- **Everything on a vehicle is ultimately air cooled**
- **Rejecting heat to air can eliminate intermediate liquid loops**
- **Air is benign and need not be carried**
- **Air is a dielectric and can contact the chip directly**
- **Enables high temperature devices**

FY13 Project-Specific Goals

- Demonstrate promising FY12 feasibility analysis at the module level with optimized design by testing with simulated electric device heat generation
- Conduct detailed analysis at system level to show progress relative to DOE technical targets

Overview

Timeline

Phase II start date: FY10

Project end date: FY15

Phase II complete: 50%

Budget

Total Project Phase II Funding:

DOE Share: $1,700K

Funding Received in FY12: $600K

Funding for FY13: $500K

Barriers

- **Cost – Eliminate need for secondary liquid coolant loop and associated cost and complexity**
- **Weight – Reduce unnecessary coolant, coolant lines, pump and heat exchangers for lower system-level weight**
- **Performance – Maintain temperatures in acceptable range while reducing complexity and system-level parasitic losses**

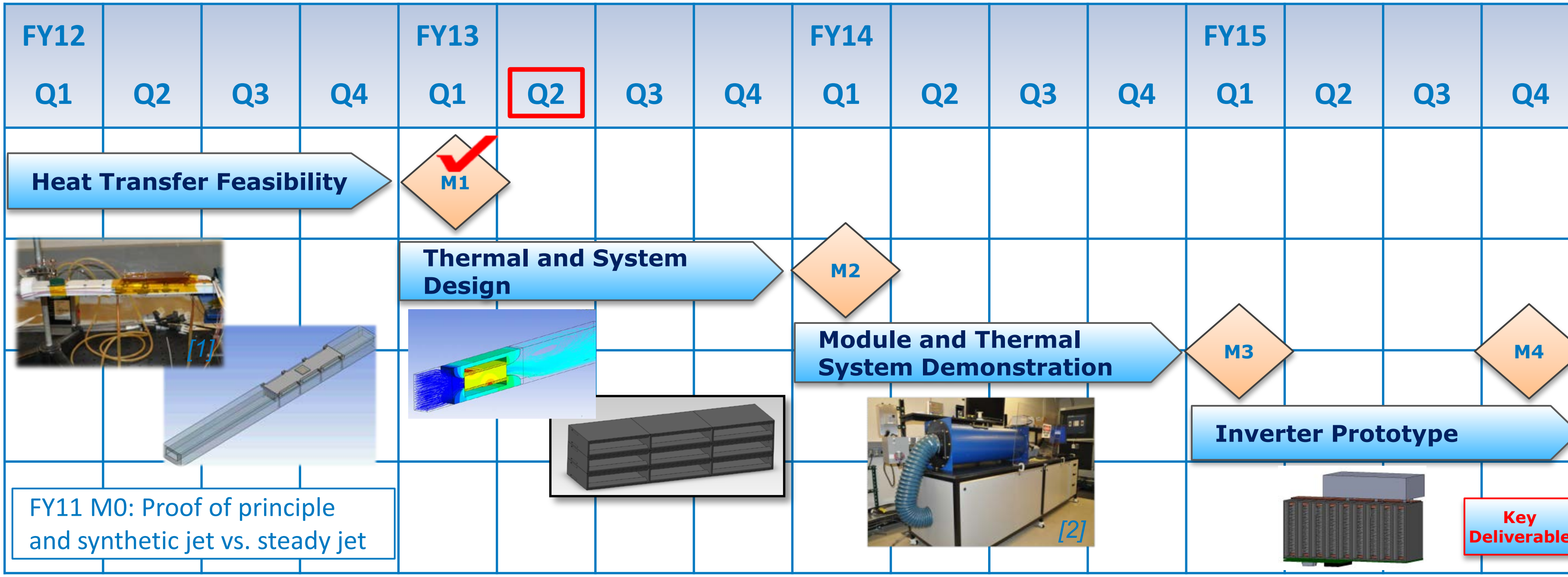
Vehicle Technologies Program 2015 Targets

12 kW/L, 12 kW/kg, $5/kW

Partners

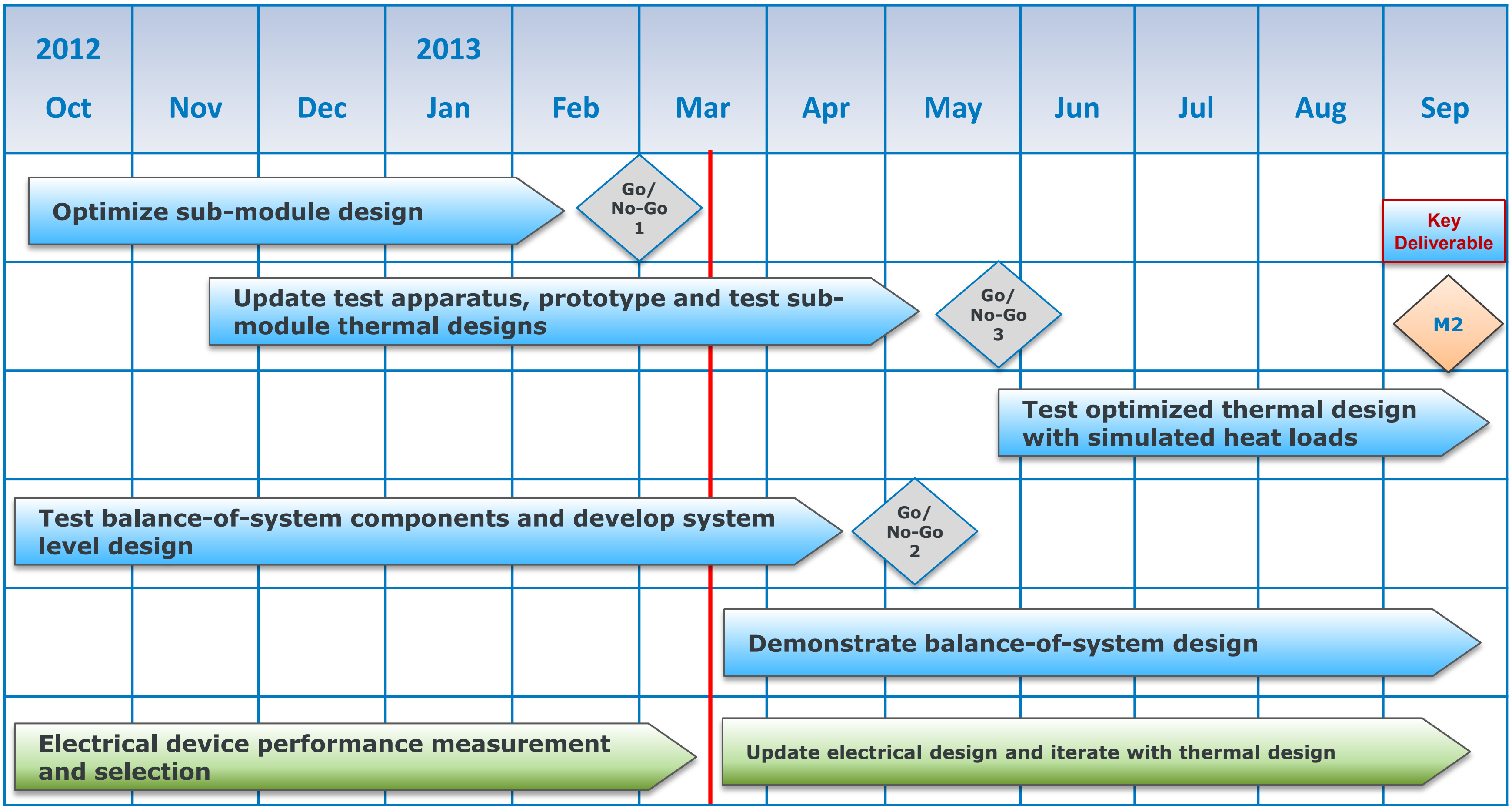
- Oak Ridge National Laboratory (ORNL)
  - Madhu Chinthavali
  - Andrew Wereszczak
- Sapa, GE, and Momentive Performance Materials

Project Summary: FY11 – FY15 Milestones



Deliverable/Milestone	Go/No Go
M1 (**NREL**): Heat transfer feasibility study M1 (**ORNL**): Device level evaluation	Heat transfer accomplished with reasonable flow and pressure loss?
M2: Build and test thermal module and initial balance-of-system M2: Module electrical design	Demonstrated design on track to meet targets?
M3: Demonstrate operating module and inverter thermal system M3: Electrical inverter design and module build	Met targets for module level? Pursue full inverter prototype build?
M4: Improve and prototype full inverter thermal system M4: Full inverter prototype build	Met 2015 targets with 55 kW inverter? Pursue concept further with industry partners?

FY13 Tasks to Achieve Key Deliverable



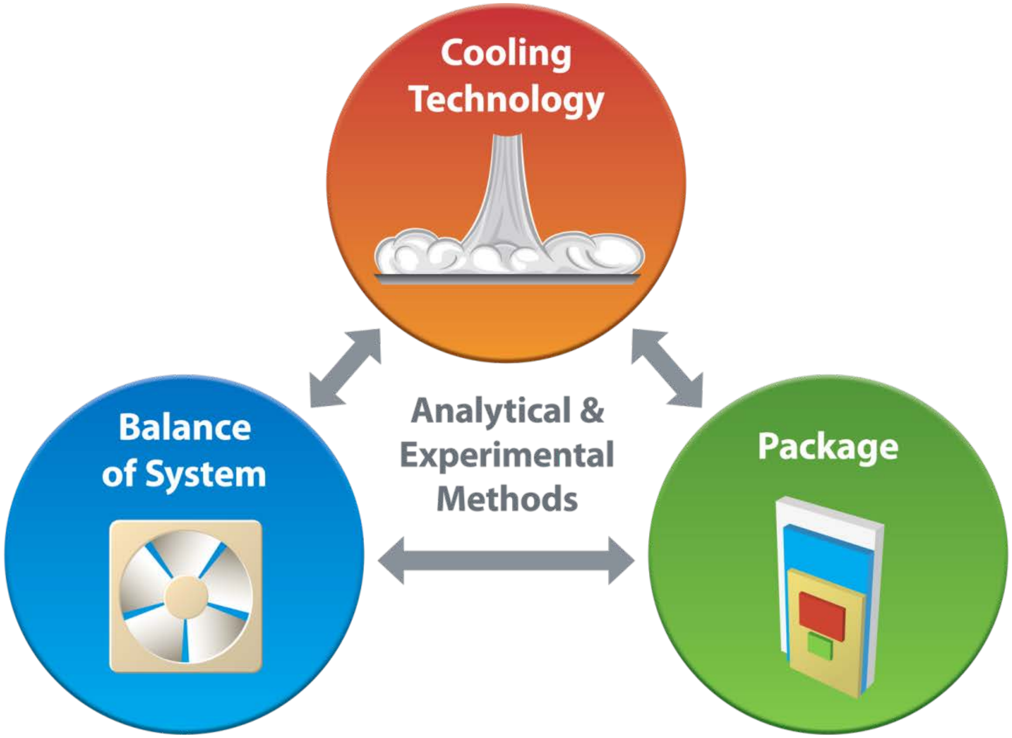
Go/No-Go 1: Optimized design is on track to meet thermal requirements? ✔

Go/No-Go 2: Balance-of-system design on track to meet air flow requirements?

Go/No-Go 3: Module thermal design on track and complete?

Key Deliverable, M2: Demonstrate feasibility of high temperature air cooled module, determine feasibility for meeting program goals

Strategy: System Approach



Thermal Environment
- Inverter Location
- Air Source

Device Type
- Max Temperature
- Efficiency

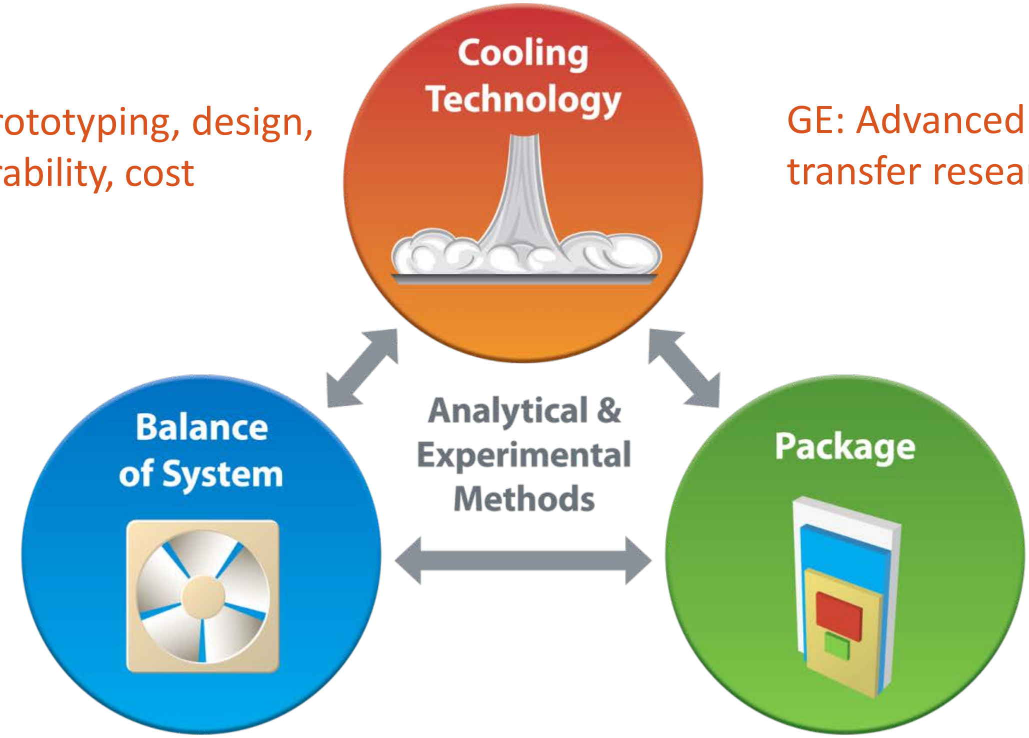
Vehicle Context
- Power/Duty Cycle
- Volume/Weight Limits

Strategy: System Approach – Partners

ORNL: Advanced device technology, electrical topology, and full system design

Sapa: Fin prototyping, design, manufacturability, cost

GE: Advanced heat transfer research (jets)



Fan technology, actively pursuing partners

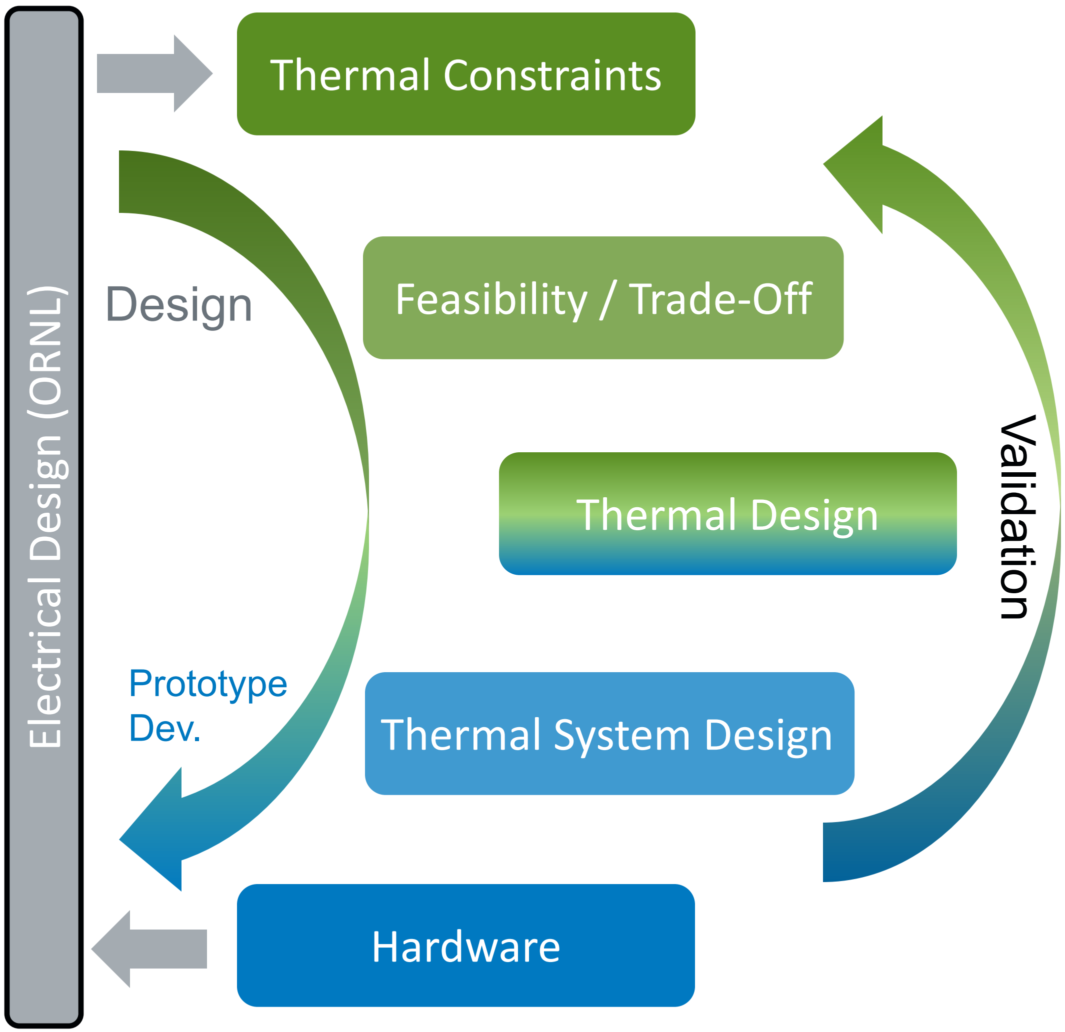
Momentive Performance Materials: Advanced materials

Thermal Environment
- Inverter Location
- Air Source

Device Type
- Max Temperature
- Efficiency

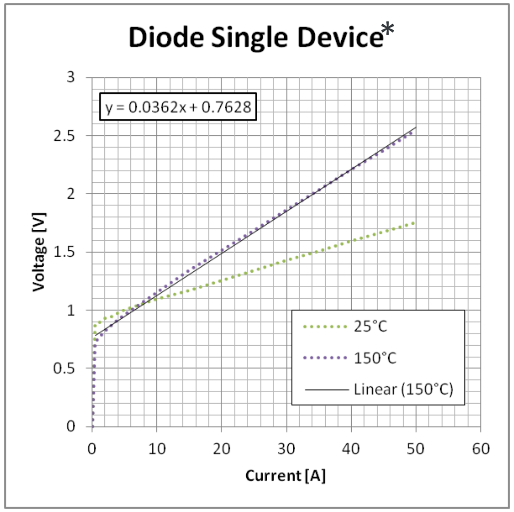
Vehicle Context
- Power/Duty Cycle
- Volume/Weight Limits

High Temperature Air-Cooled Inverter



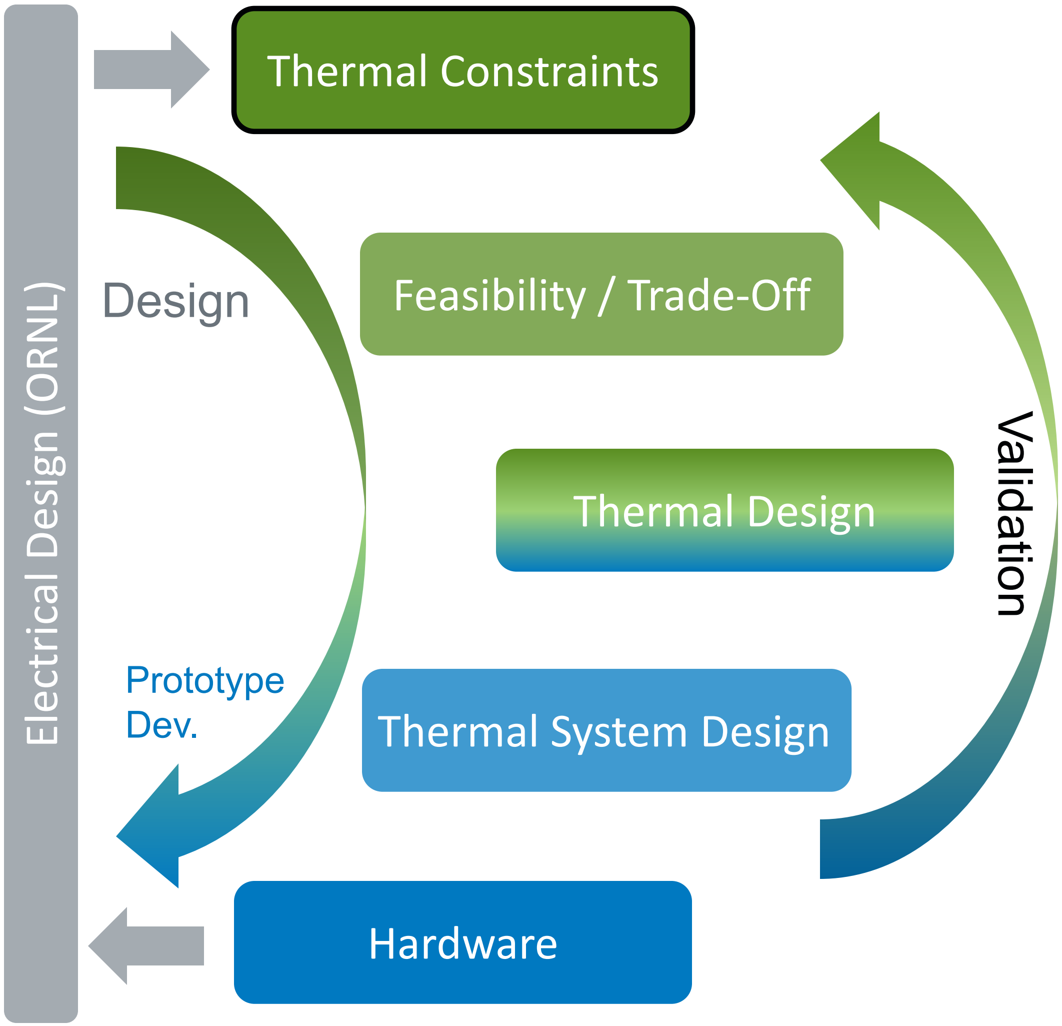
Electrical Design

- **Device type**
- **Device locations**
- **Electrical duty cycles**
- **Temperature-dependent loss equations**
- **Inverter efficiency**



**Chinthavali, M. "Wide Bandgap Materials." Section 2.1. DOE 2010 Annual Progress Report for Advanced Power Electronics and Electric Motors. Susan A. Rogers. January 2011.*

High Temperature Air-Cooled Inverter



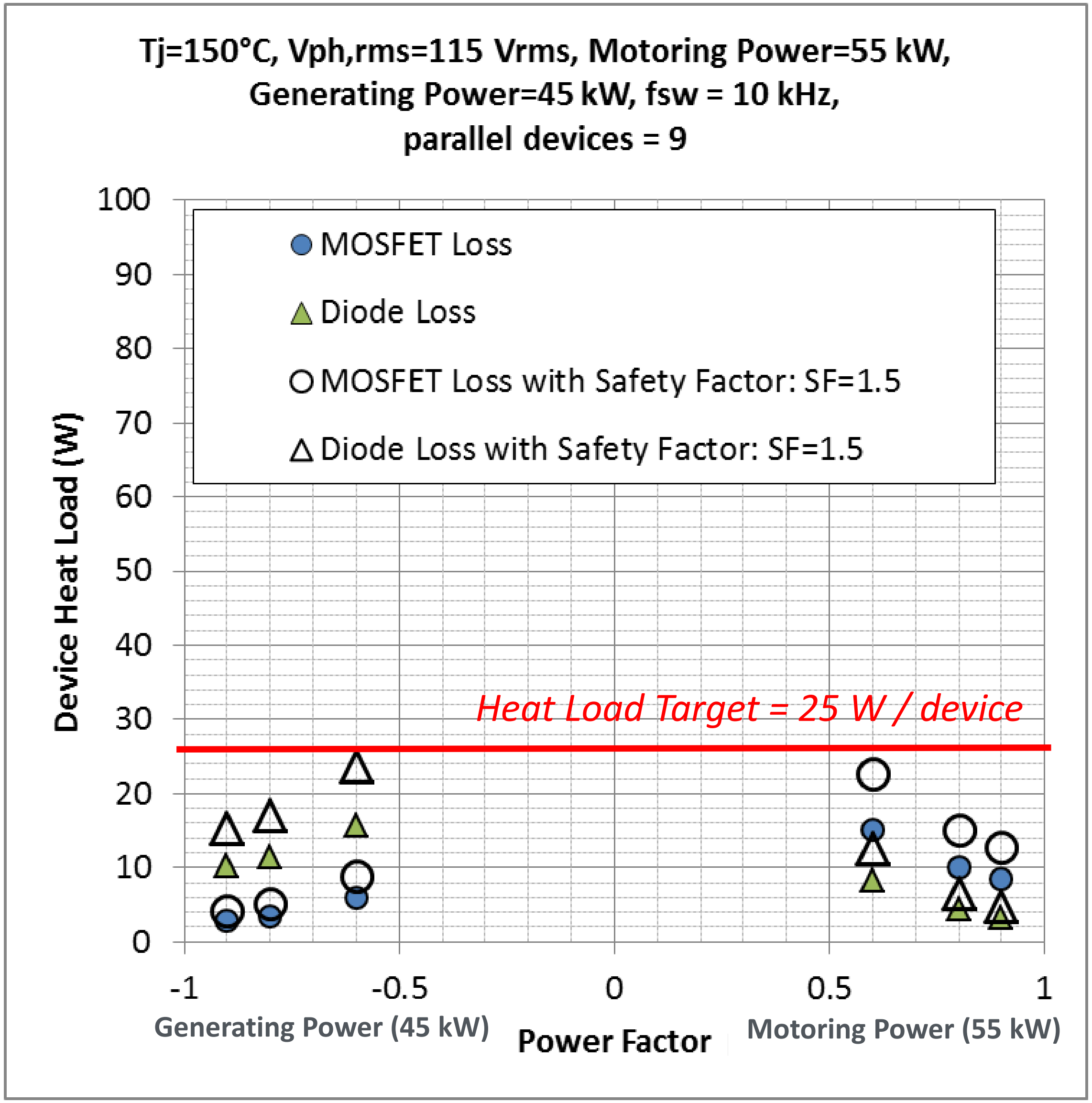
Thermal Constraints

- **Maximum junction temperature**
- **Heat generation**
  - Efficiency estimate
  - Analytical method
  - Switching model
- **Coolant temperature**

Heat Generation: 9 parallel devices

Target 2.7 kW heat, 95% efficient at 55 kW electrical

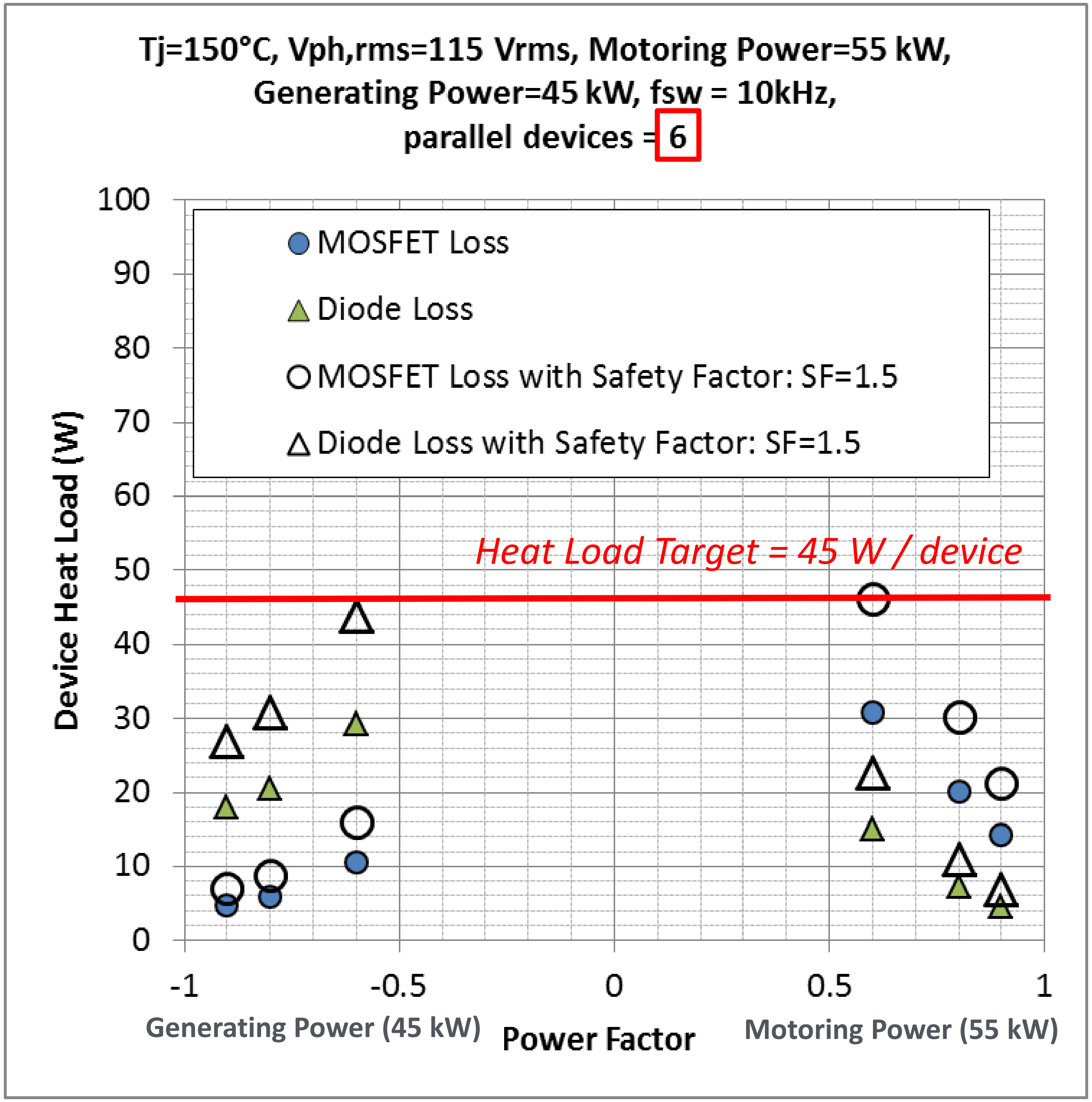
- **Device data from ORNL**
- **Standard analytical equations**
- **Heat loads will vary with operating conditions**
  - Conservative current operation condition
  - Conservative power factor
- **Applied 1.5 safety factor to MOSFET heat loss for heat load target**
- **Used heat load target for all devices**



Heat Generation: 6 Parallel Devices

Target 3.24 kW heat, 94% efficient at 55 kW electrical

- **Device data from ORNL**
- **Standard analytical equations**
- **Heat loads will vary with operating conditions**
  - Conservative current operation condition
  - Conservative power factor
- **Applied 1.5 safety factor to MOSFET heat loss for heat load target**
- **Used heat load target for all devices**



High Temperature Air-Cooled Inverter

Electrical Design (ORNL)

Thermal Constraints

Design

Feasibility / Trade-Off

Thermal Design

Validation

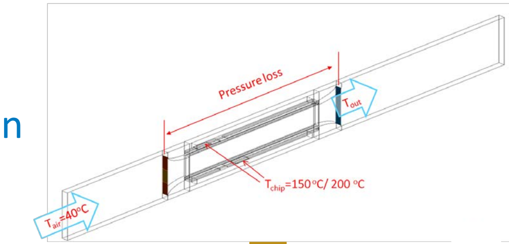
Prototype Dev.

Thermal System Design

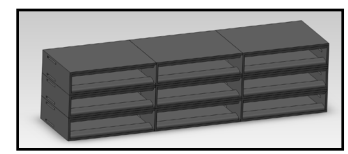
Hardware

Feasibility/Trade-off

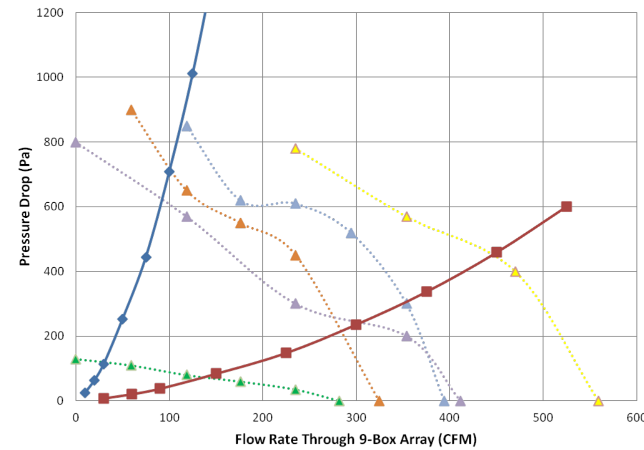
Single Fin CFD



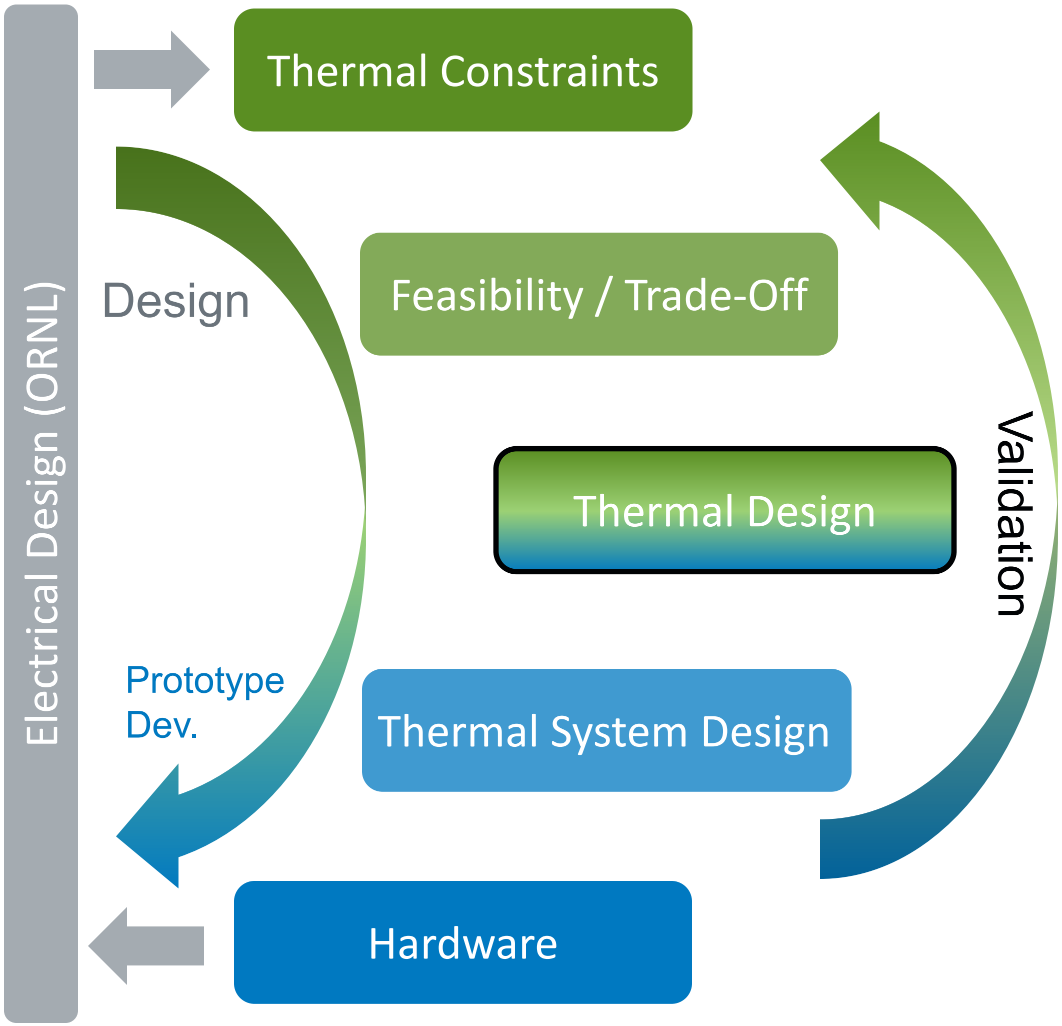
Extrapolate system



Add fan

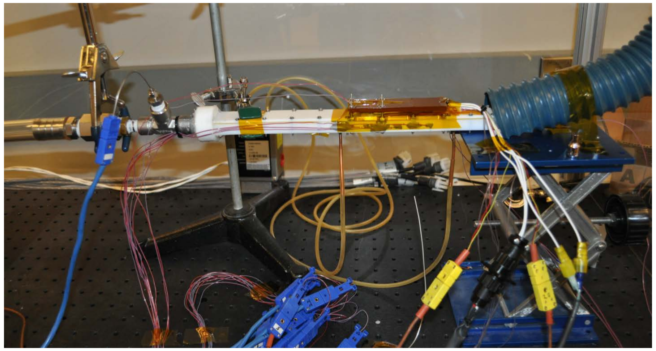


High Temperature Air-Cooled Inverter

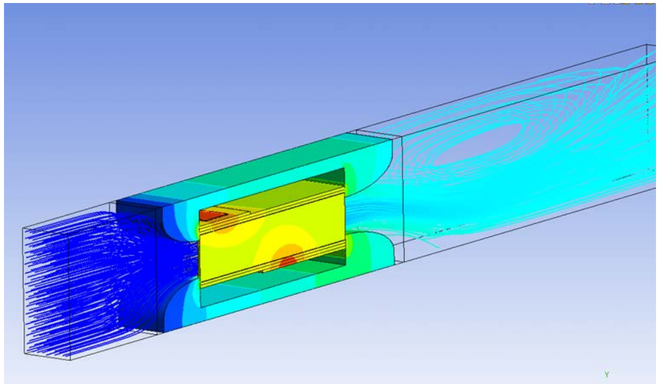


Thermal Design

Design concept and balance-of-system testing



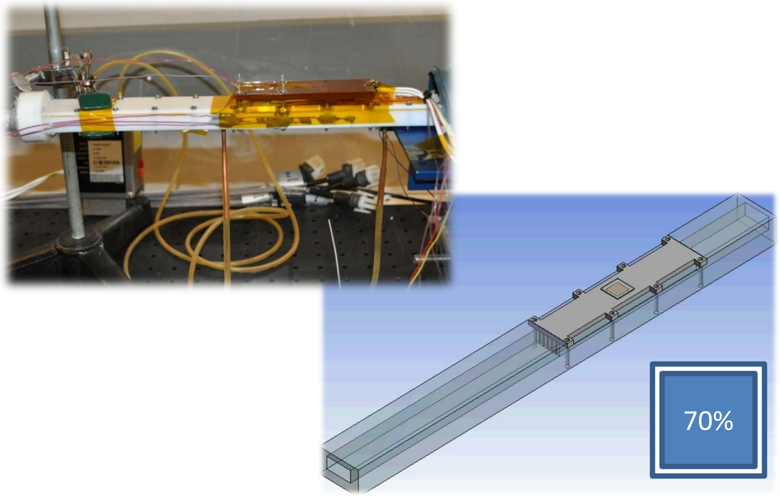
Model validation and design optimization



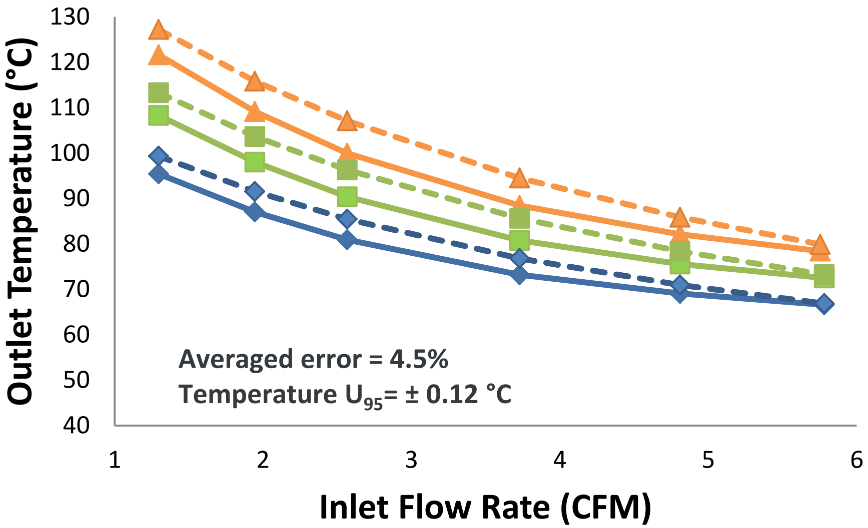
Model Validation

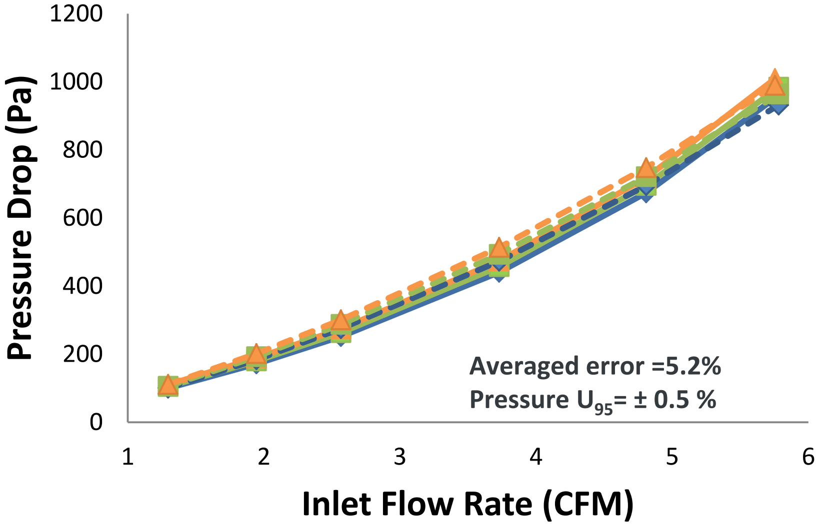
Less Than 6.5% error between model and experiment

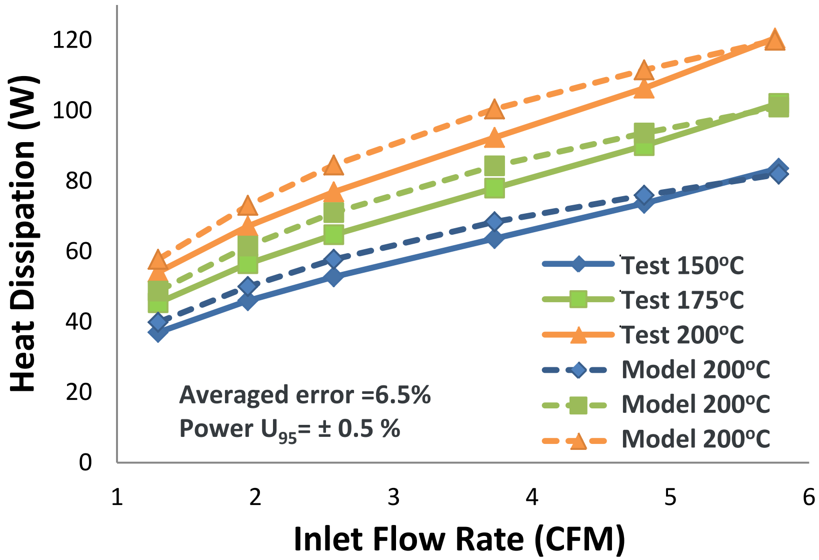
FY12/Milestone 1



- Chip temperature: 150°C, 175°C, 200°C
- 5 W/m^{2}K heat transfer coefficient at the exterior walls
- 70% thermal contact between device and fin







Module Design Improvement

Sub-module computational fluid dynamics optimization

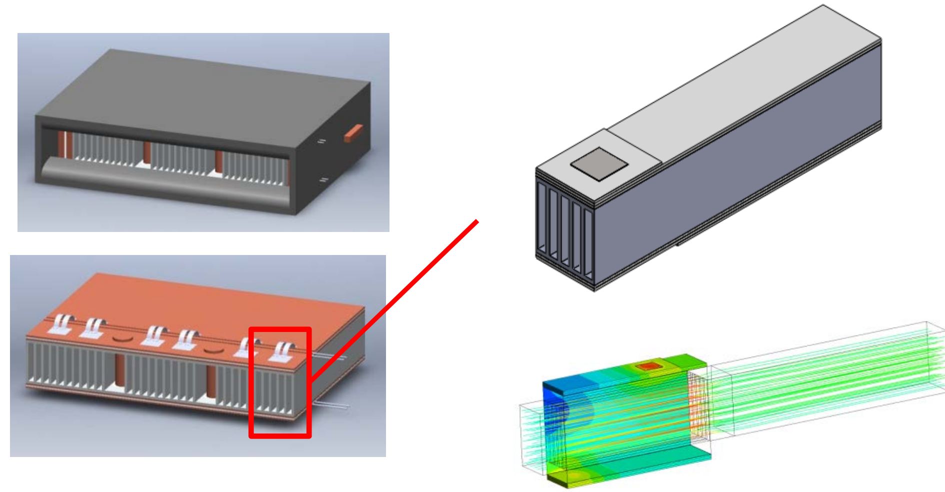
Design Constraints

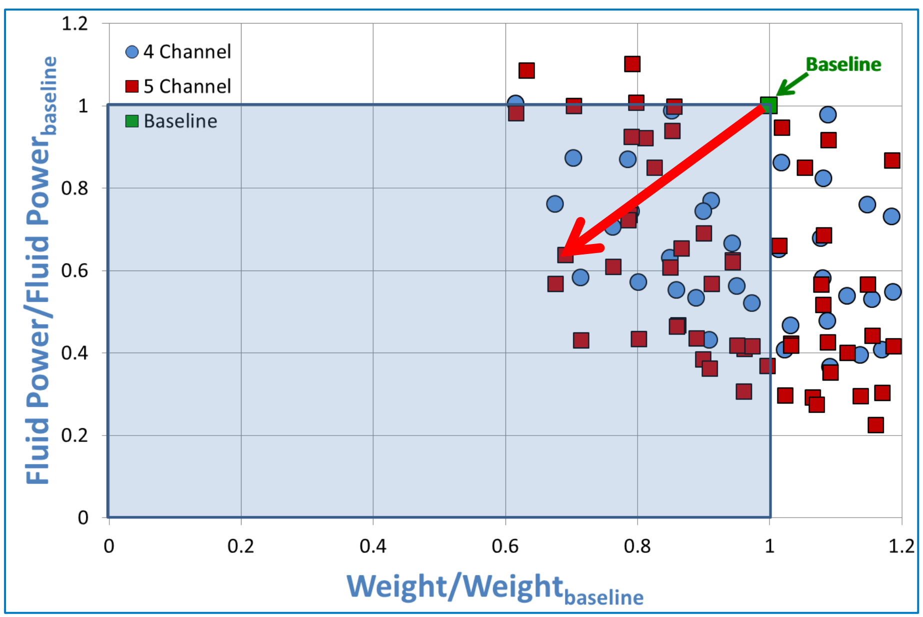
- Heat dissipation
- Device temperature

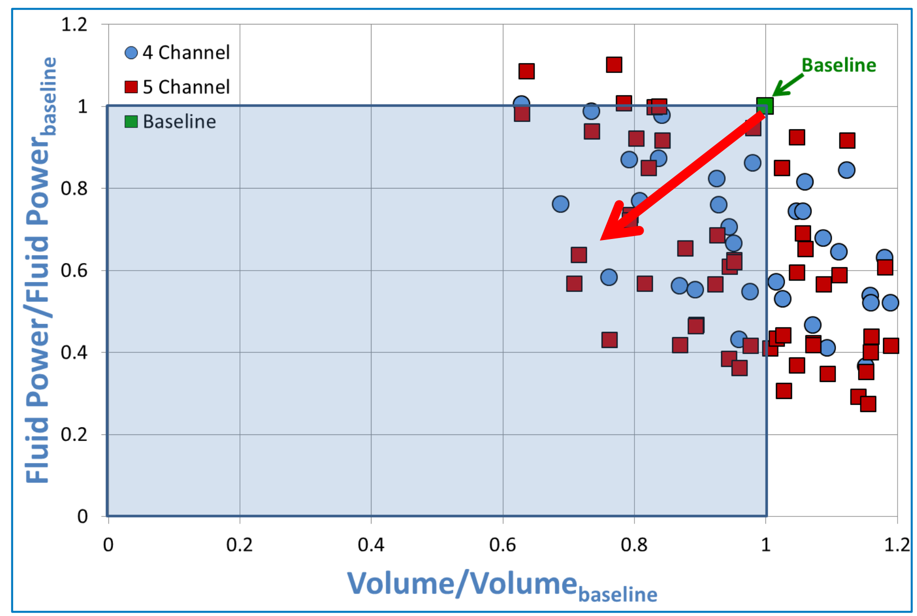
Optimization Parameters

- Device location
- Fin thickness
- Channel width
- Base plate thickness
- Fin height
- Fin length

Fluid Power

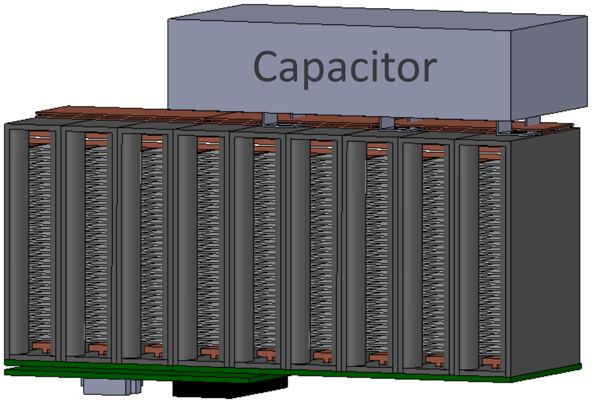


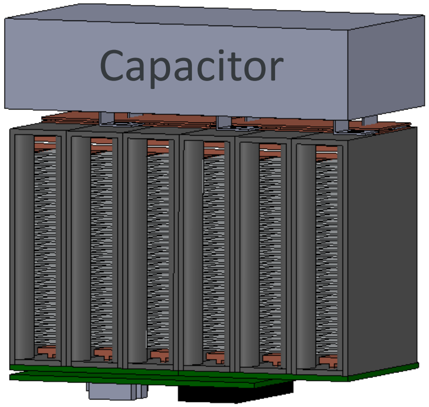




Balance-of-Inverter Assumptions

Impacts volume, weight, and electrical power

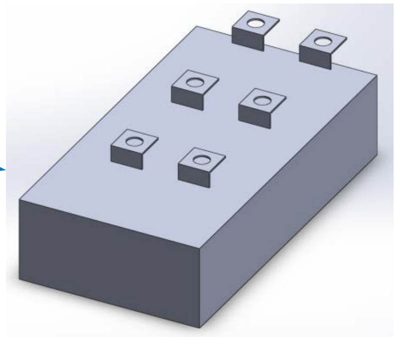


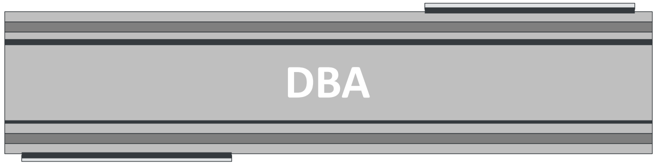


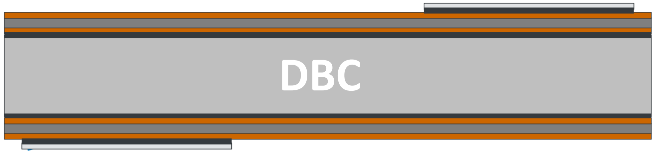
- 55 kW electrical power assumed
- 25 W per device heat dissipation (2.7 kW)

- 55 kW electrical power assumed
- 45 W per device heat dissipation (3.2 kW)

- Casing volume adjusted for fin geometry
- Capacitor ~ 1.13 L[1], ~1.35 kg[*]
- Gate driver + control board ~0.88 L[*], ~ 0.34 kg[**]
- Direct-bond copper (DBC) and Direct-bond aluminum (DBA)





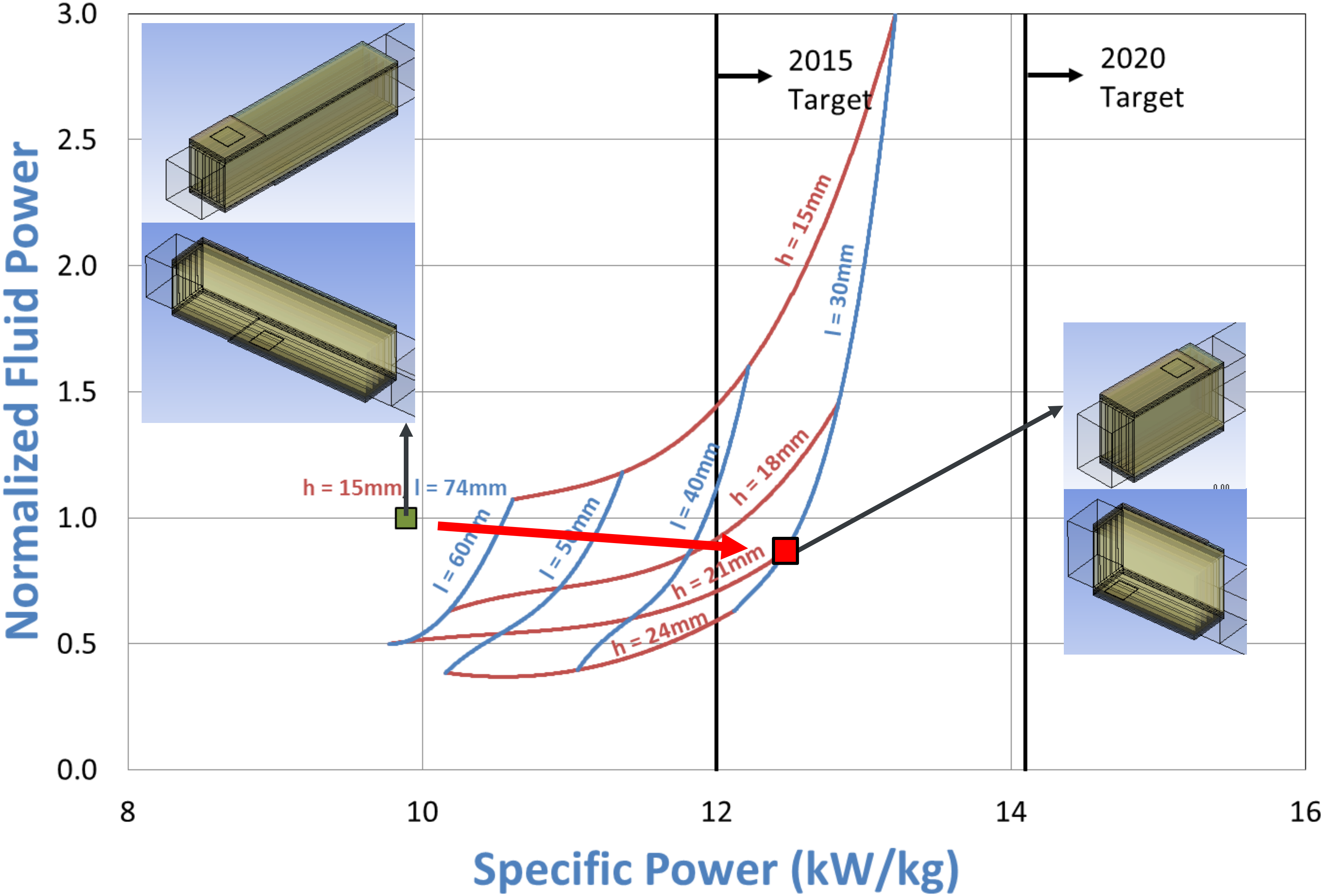


*: Assumption provided by ORNL, **: NREL assumption based on similar device measurement

Optimized Geometries Improve Specific Power

On track to meet DOE 2015 technical target

FY13 – Go/No-Go 1

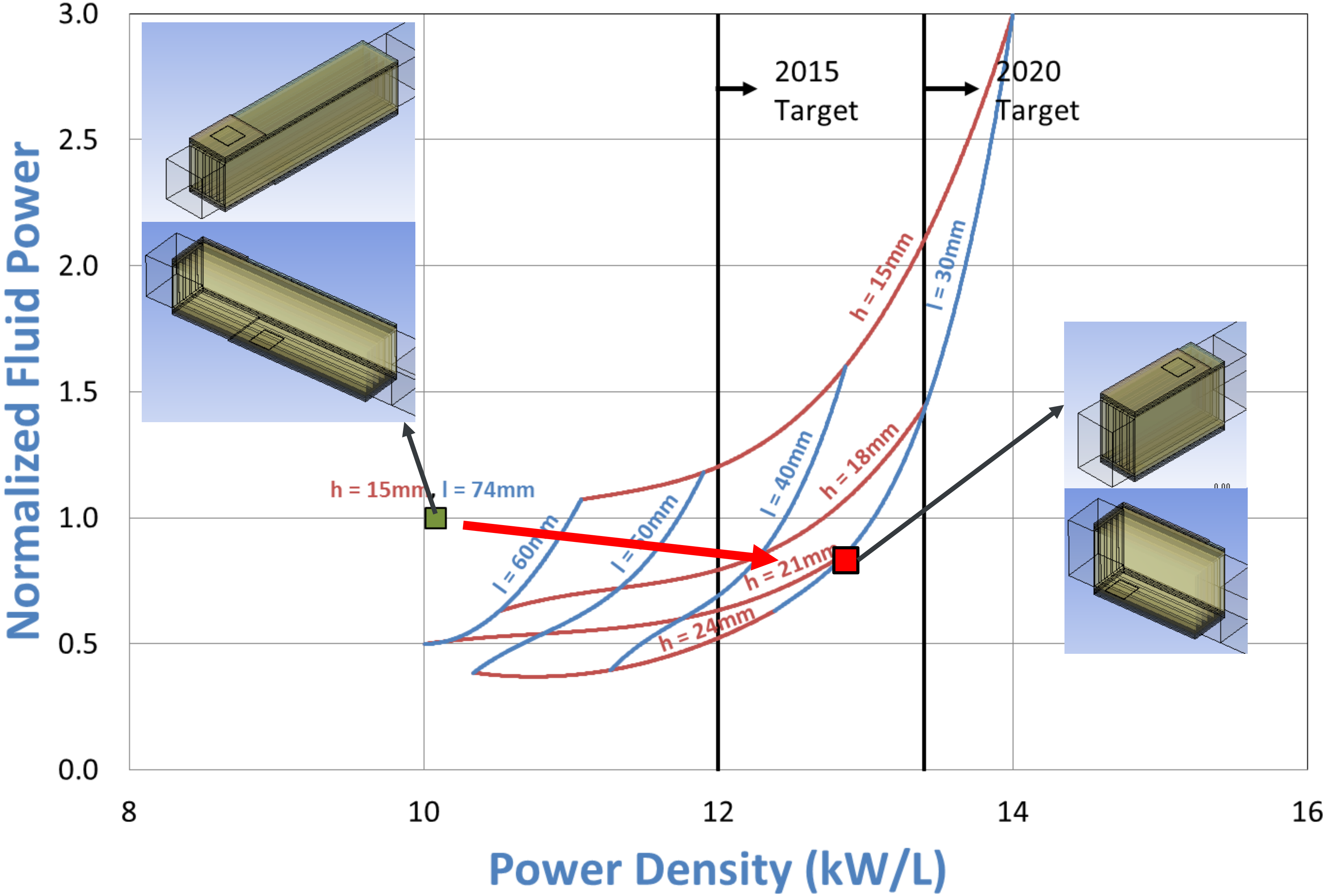


9 module, DBC

Optimized Geometries Improve Power Density

On track to meet DOE 2015 technical target

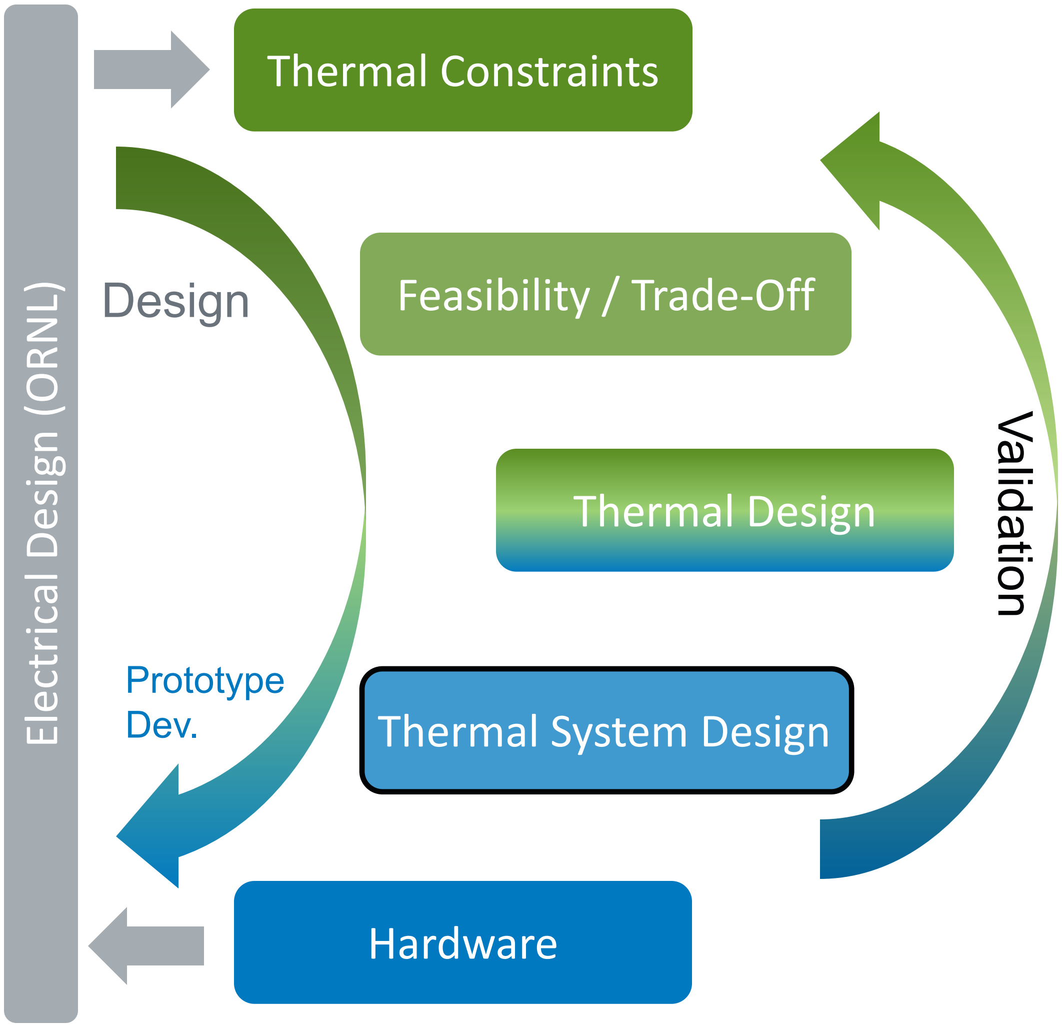
FY13 – Go/No-Go 1



9 module, DBC

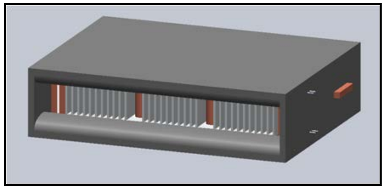
High Temperature Air-Cooled Inverter

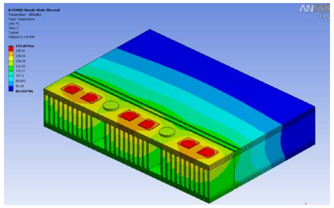
FY13 Go/No-Go 2

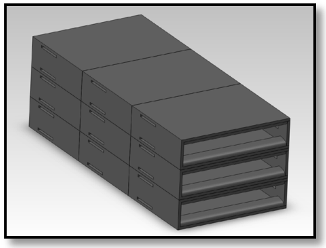


Thermal System Design

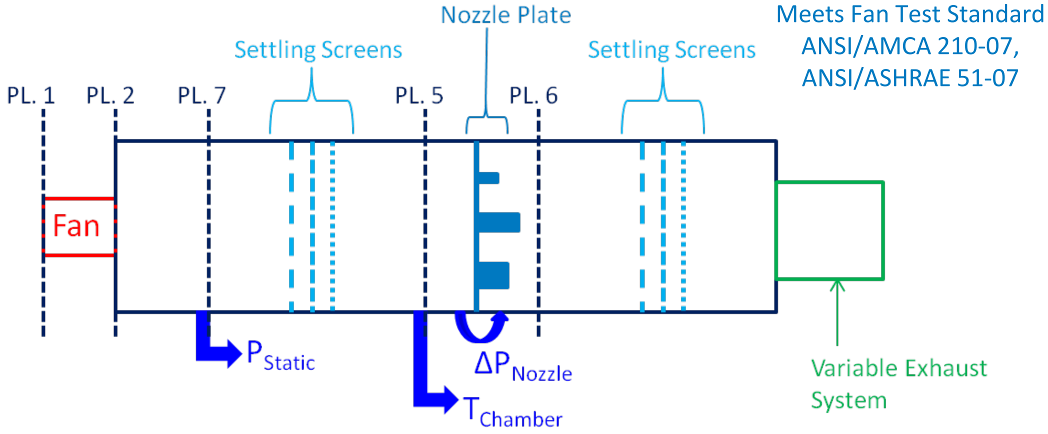
- **Balance-of-system design**
- **Couple module model to balance-of-system test results**
- **Full system level models**
- **Design drawings to build thermal management prototype**



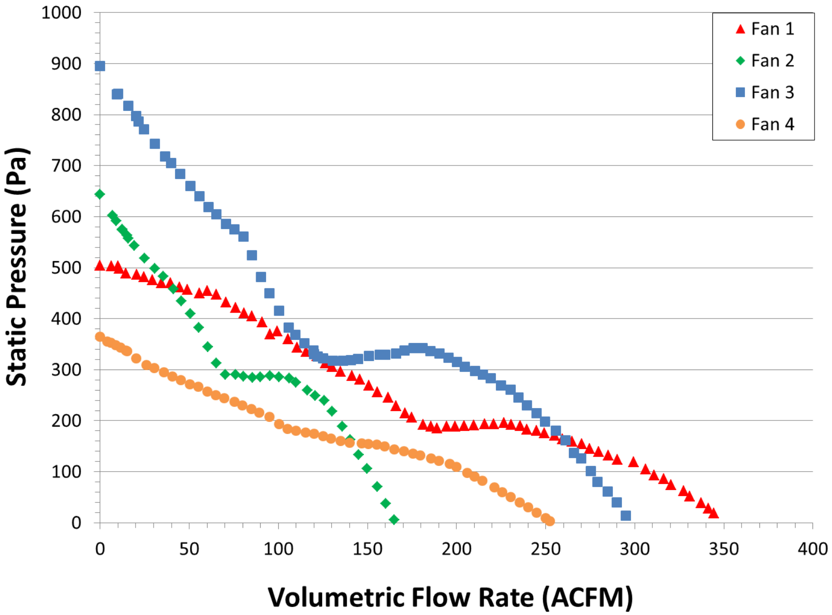


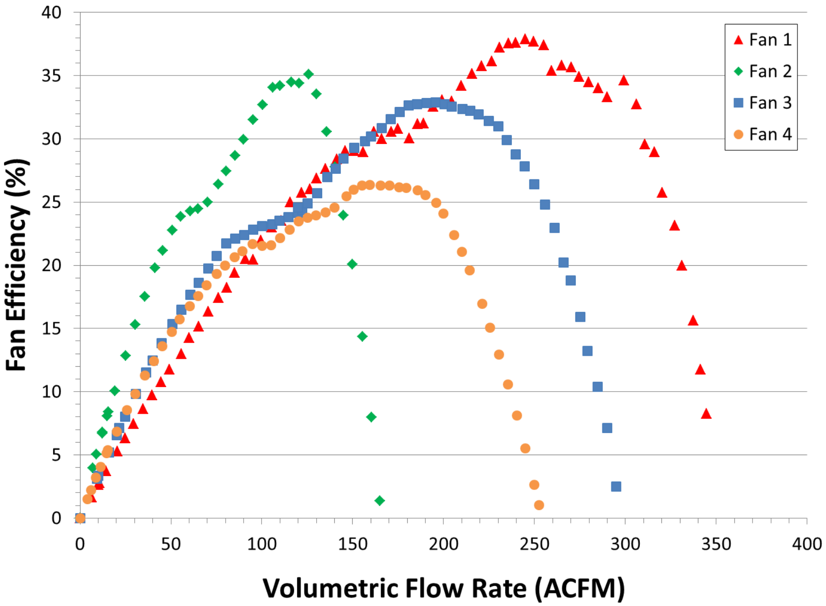


System-Level Test Bench



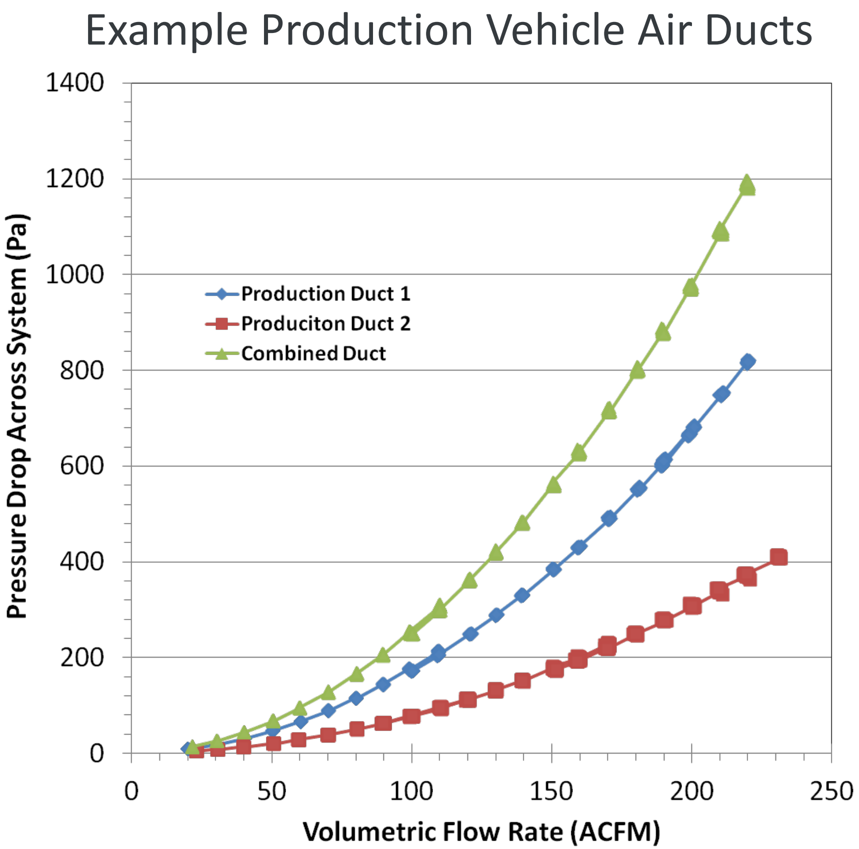
- Range: 5–500 CFM
- U-95 Flow: ±1.5 CFM, U-95 Pressure: ±1.6 Pa



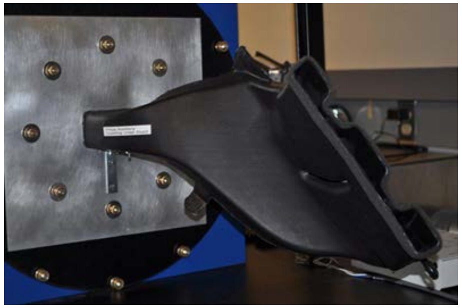


Balance of System: Ducting Design

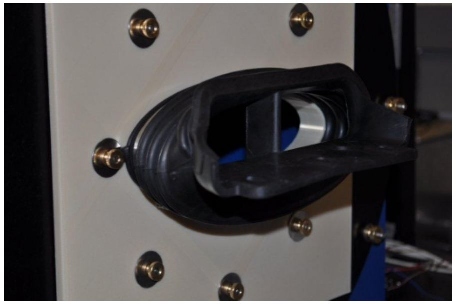
Pressure loss and location options



Production Duct 1



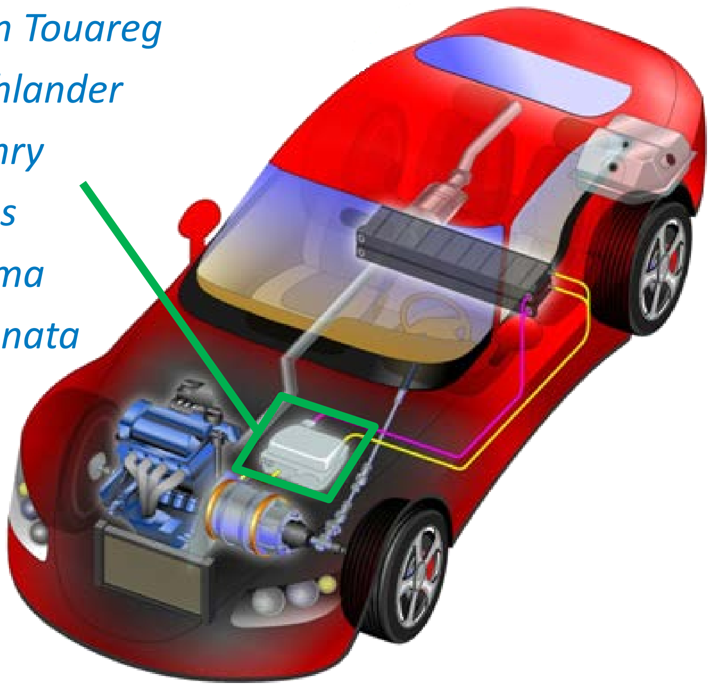
Production Duct 2



[1]

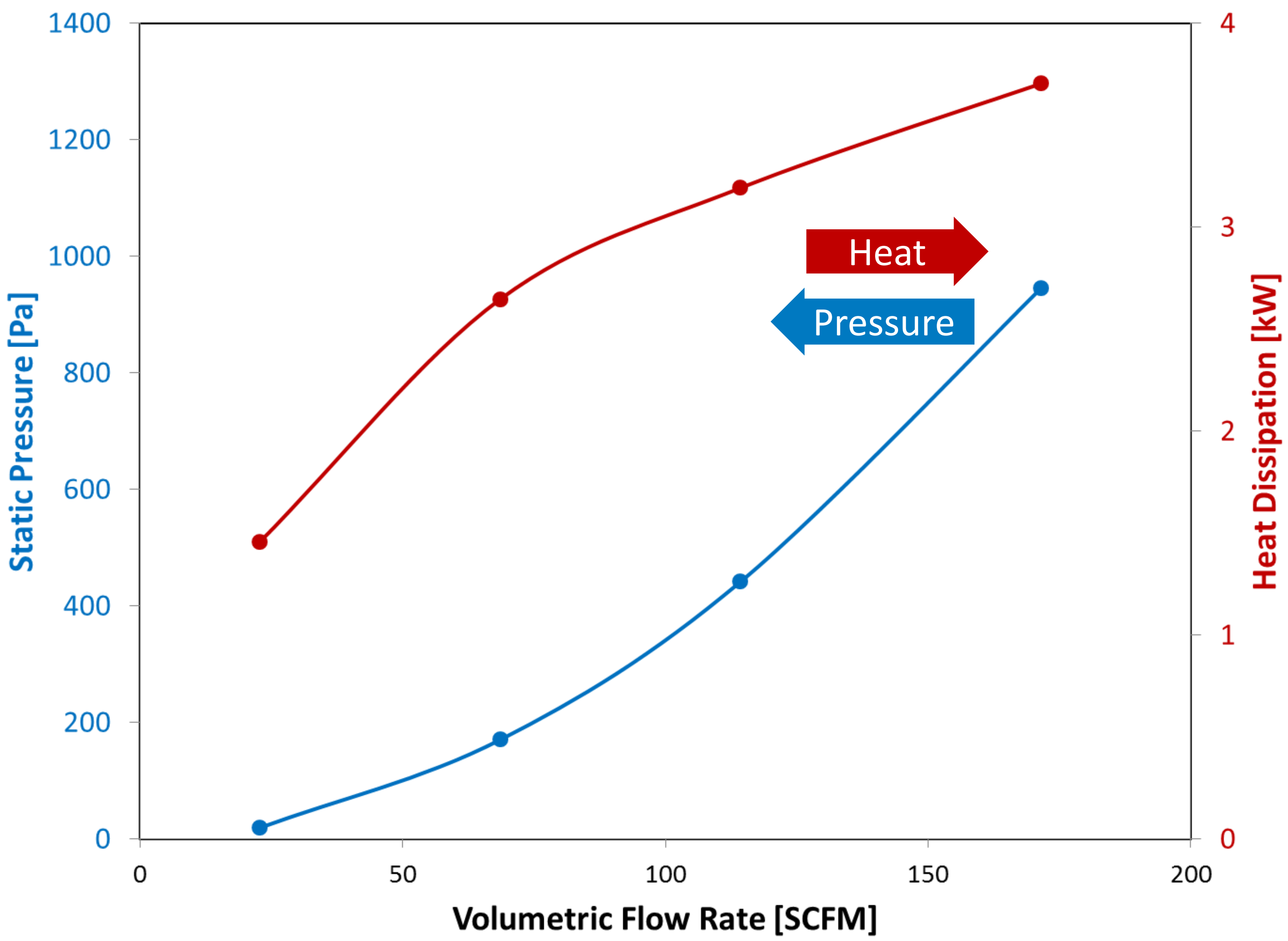
Inverter Location

Volkswagen Touareg
Toyota Highlander
Toyota Camry
Toyota Prius
Nissan Altima
Hyundai Sonata
Chevy Volt



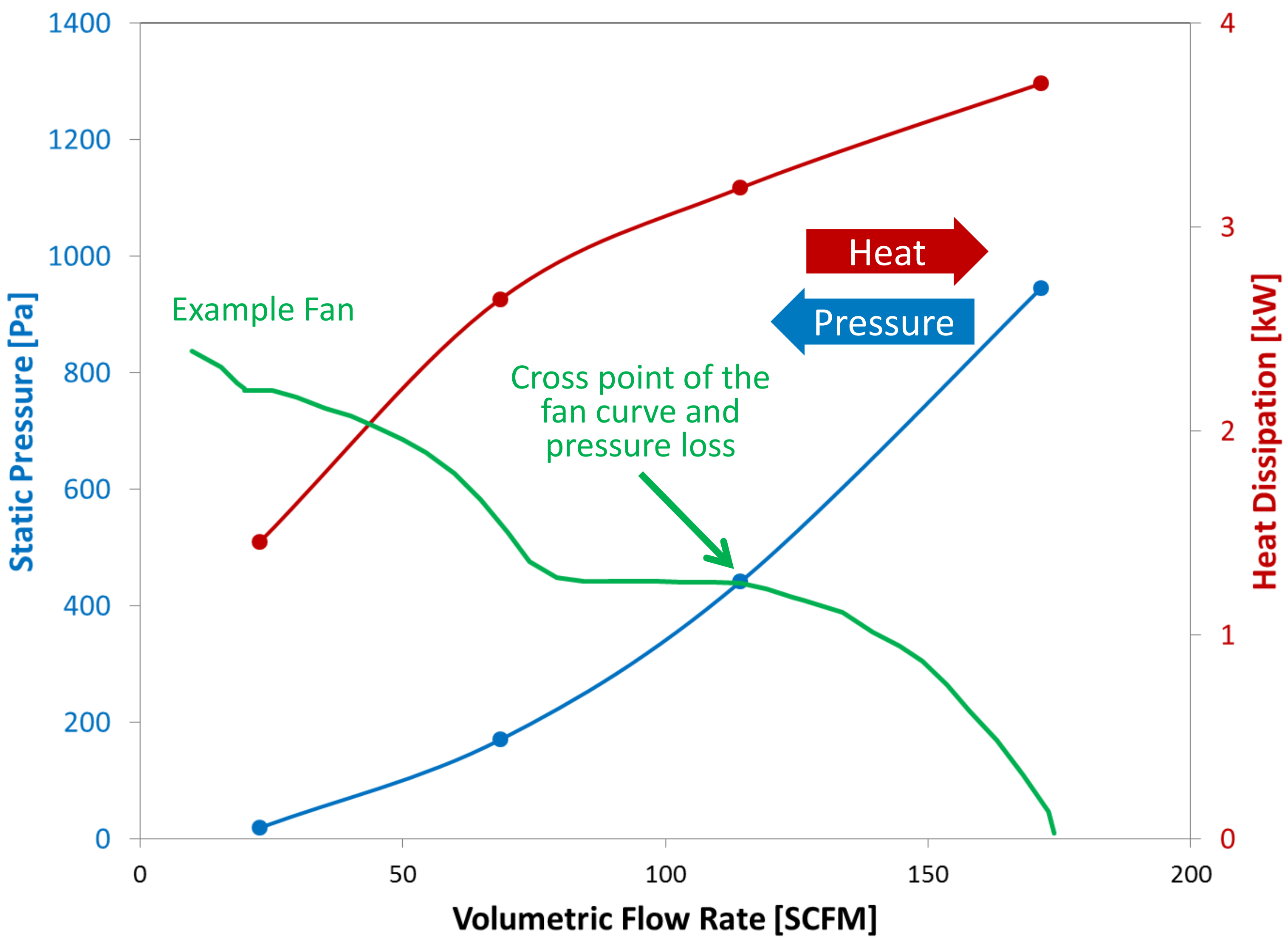
Example System Flow Study

9-by-1 array design, DBC, and 175°C



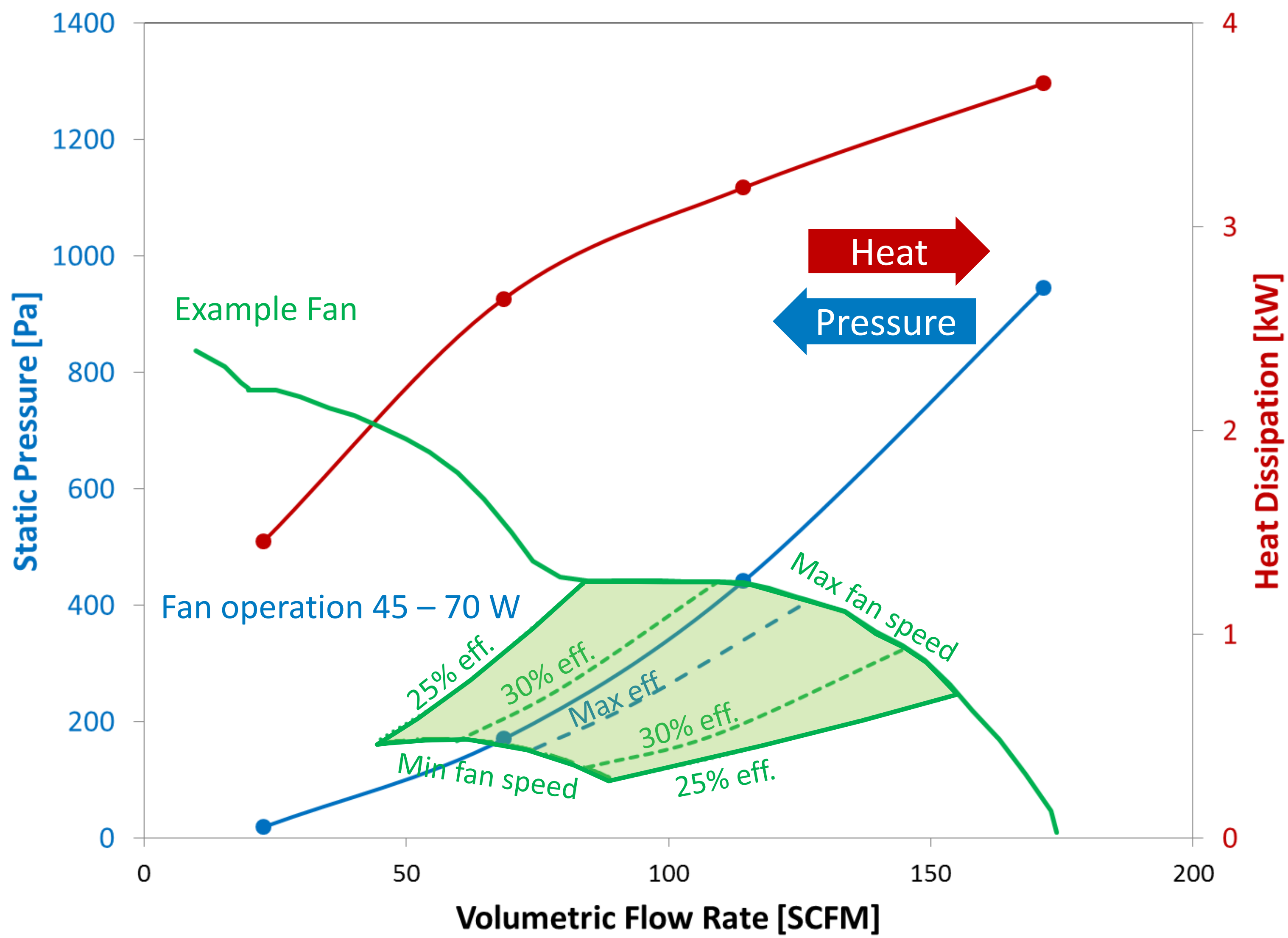
Example System Flow Study

9-by-1 array design, DBC, and 175°C



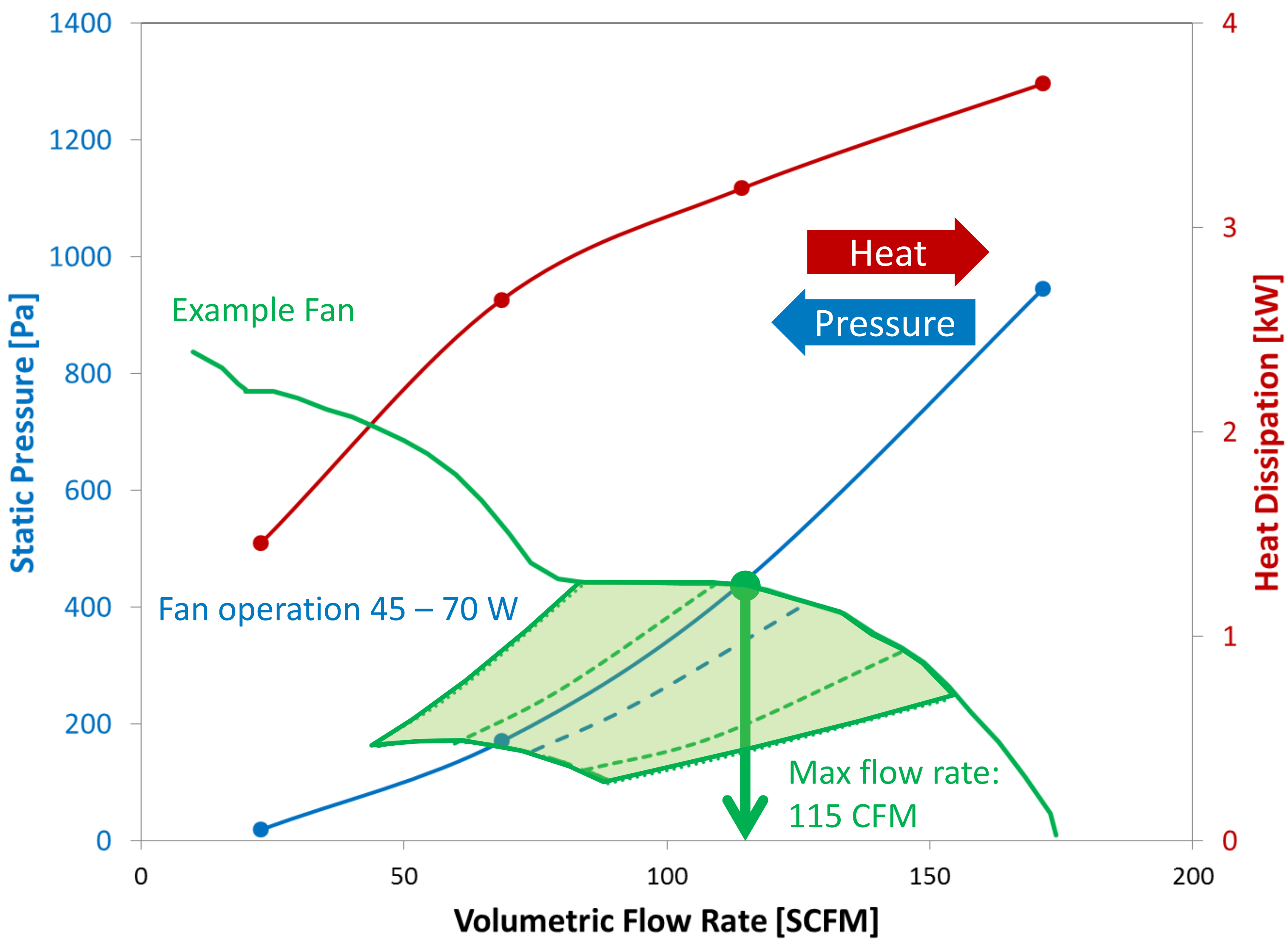
Example System Flow Study

9-by-1 array design, DBC, and 175°C



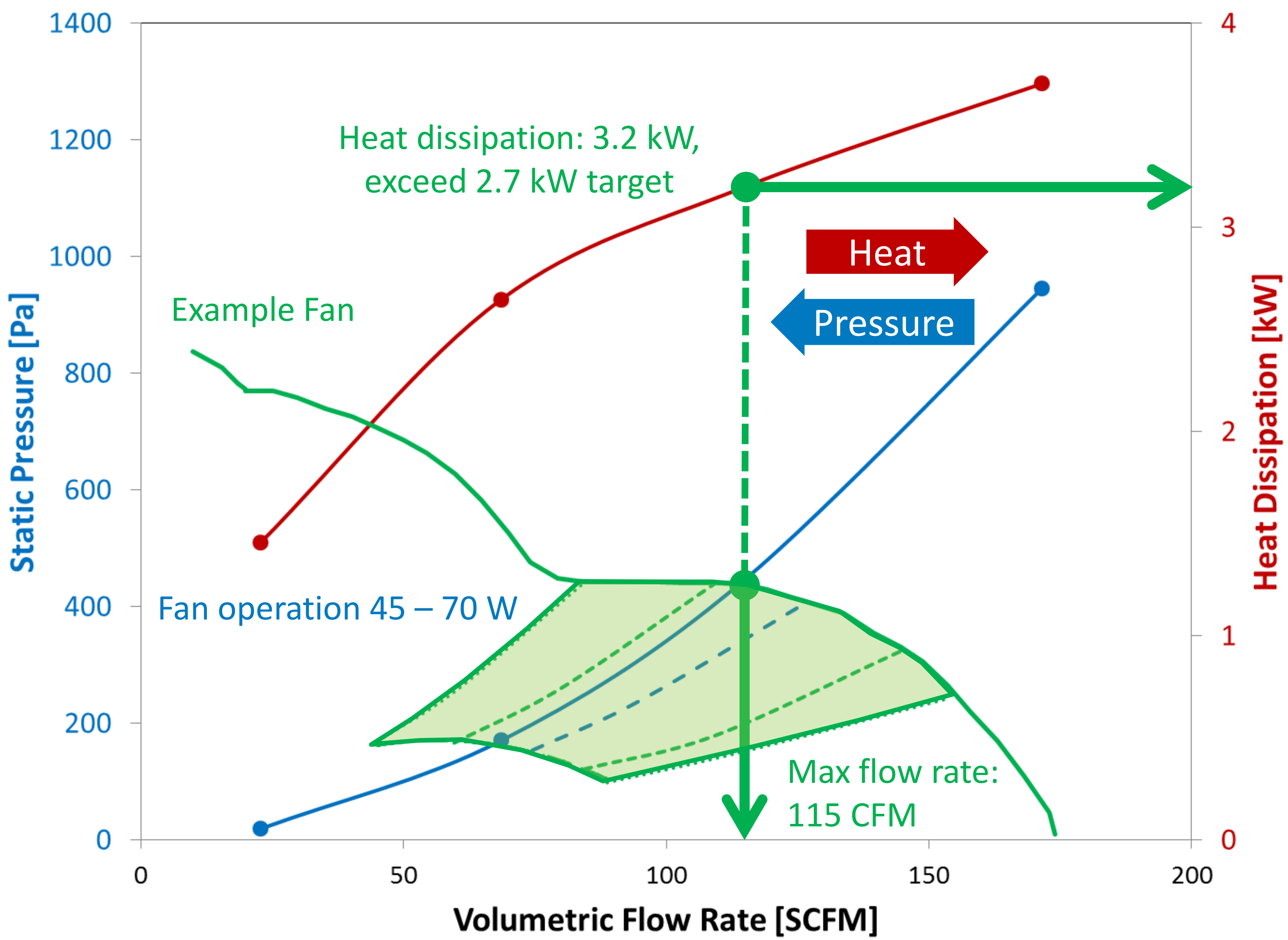
Example System Flow Study

9-by-1 array design, DBC, and 175°C



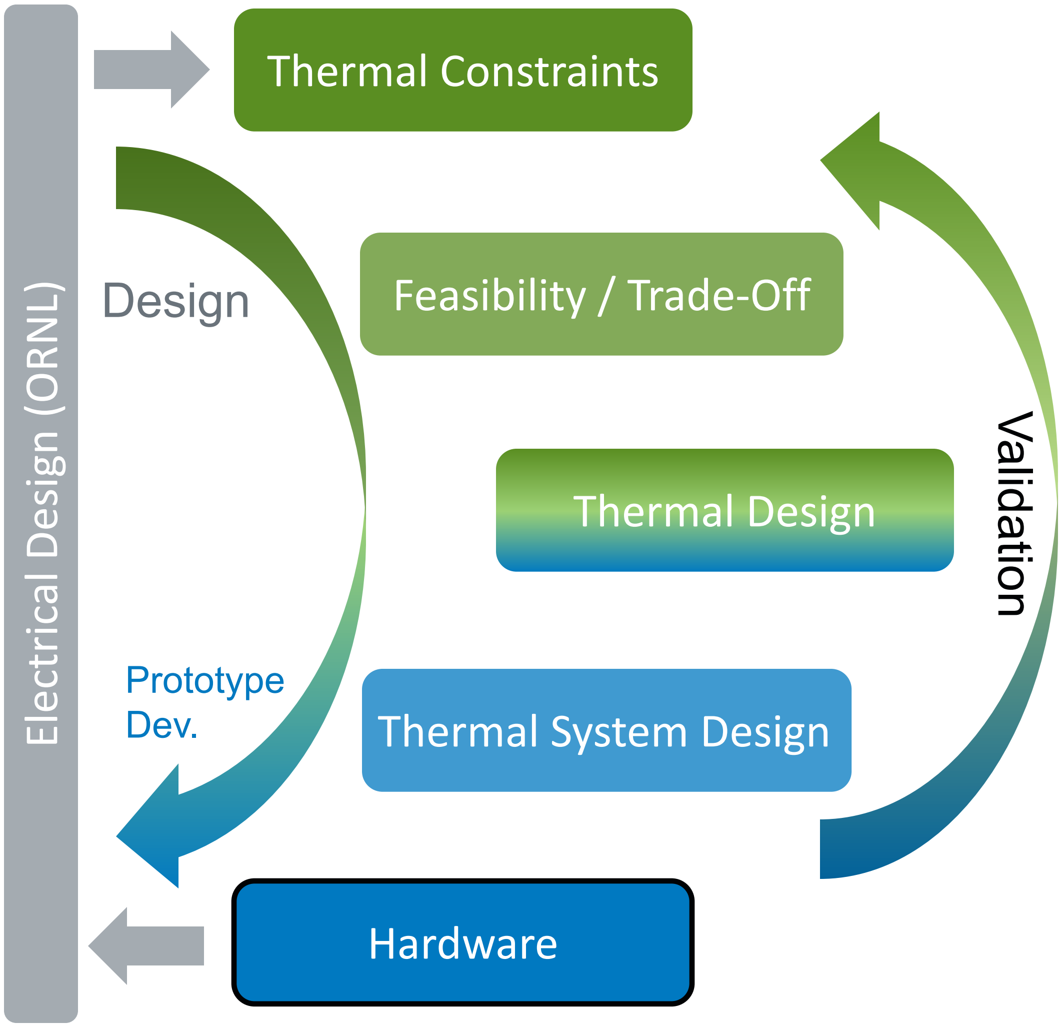
Example System Flow Study

9-by-1 array design, DBC, and 175°C



High Temperature Air-Cooled Inverter

FY13 Go/No-Go 3



Hardware

- **Build prototype thermal management system and test on bench**
- **Use results to feed back and improve design**
- **Determine progress toward 2015 goals**

Future Work

- FY13
  - Validate sub-module model results
  - Build and test air-cooled module-level thermal management system.
  - Test balance-of-system proof of concept
  - Projected Go/No-Go Decision Point: If projected results meet the DOE inverter target for volume and weight, pursue module build
- FY14
  - Work with ORNL to build and test lower power high temperature air-cooled inverter system (one SiC module by 4/14)
  - Build and demonstrate full system thermal management system
  - Projected Go/No-Go Decision Point: If test results are on track to meet DOE inverter targets for volume and weight, pursue full inverter build
- FY15
  - NREL to finalize and prototype inverter thermal management system
  - ORNL to finalize and prototype inverter electrical system
  - NREL and ORNL demonstrate full inverter operation, quantifying performance
  - Projected Go/No-Go Decision Point: If test results meet DOE 2015 inverter targets for volume and weight, then pursue full vehicle-level demonstration with industry partners

Summary

DOE Mission Support

- Overcome barriers to adoption of low-cost air-cooled heat exchangers for power electronics; air remains the ultimate sink.

Approach

- Create system-level understanding and designs addressing advanced cooling technology, balance of system, and package thermal interactions; develop solutions from fundamental heat transfer, then system level design, to application – culminating in vehicle-level viability demonstration with research partners.

Summary

Technical Accomplishments

- Optimized thermal design showing improvements in weight, volume, and power density can help meet DOE technical targets
- Showed though computational fluid dynamics modeling that the high temperature air-cooled inverter is on track to meet DOE 2015 specific weight and power density targets
- Tested production balance-of-system components and showed feasibility, now researching design options

Collaborations

- Strengthened collaboration with ORNL for collaborative high-temperature air-cooled inverter project
- Researching advanced air-cooling technology in collaboration with Sapa, GE, and Momentive
- Working on adding a fan manufacturer collaboration

Acknowledgments and Contact

Acknowledgments:

- Susan Rogers and Steven Boyd
  U.S. Department of Energy

- Madhu Sudhan Chinthavali & Andrew Wereszczak
  Oak Ridge National Laboratory

Team Members:

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[1]

References

Slide 2

1. Honda Insight photograph: John P. Rugh, NREL
2. Honda power electronics photograph: Oak Ridge National Laboratory
3. Electric Mini Cooper photograph: DOE Advanced Vehicle Testing Activity & Idaho National Laboratory
4. AC Propulsion AC-150 photograph: Jason A. Lustbader & Dean Armstrong, NREL

Slide 5

1. Device Level Test Bench: Xin He, NREL
2. System Test Bench: Casey Smith, NREL

Slide 22

1. Test bench photograph: Casey Smith, NREL

Slide 28

1. Duct photographs: Casey Smith, NREL

Slide 32

1. NREL photographs: Dennis Schroeder, NREL Image Gallery 19050